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THE PROPAGATION OF AIR SHOCK WAVES ON A BIOPHYSICAL MODEL

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THE PROPAGATION OF AIR SHOCK WAVES ON A BIOPHYSICAL MODEL

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ABSTRACT

Shock wave characteristics were studied in the field about and within the Rhesus monkey body form. Measurements were obtained in free air, top of the animal's head, the mid-brain and the lower thorax; with distance and position of the explosive varied in relation to the animal's body. The study of shock wave transmission from one body level to another was accomplished and the problem complexity of shock wave energy distribution in the field of the organism was emphasized. Shock wave forms were observed to be uniquely characteristic of the medium through which shock wave transmission occurred. In addition, body tissue was found to greatly attenuate the shock wave. The study of shock wave characteristics in and about biophysical media is believed to be relatively unexplored.

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THE PROPAGATION OF AIR SHOCK WAVES

ON A BIOPHYSICAL MODEL

INTRODUCTION

There has been a steady progress in the development of methods and techniques whereby the shock wave can be studied about and within animal bodies with ever greater accuracy. Through studies, where the shock wave assumes new characteristics as it passes through a biophysical medium, we may acquire a better understanding of relationships between the blast factors and psychological and physiological functions of blast exposed humans.

A number of significant contributions have been made since World War II towards a general understanding of shock wave reaction with biological organisms. Using a high speed X-ray technique, Clemedson, et al, (3), were able to visualize a high explosive shock wave in muscular tissues as a zone of increased density. The density of the intense shock wave, however, must be of great enough magnitude to be detectable by this method. The above authors think that the 15-1500 psi pressure range, significant from the physiological point of view, is not likely to yield the density distinguishable by this technique.

With the aid of Schlieren photography, Clemedson and his colleagues (4) obtained records of the impact and reflections of a high explosive shock wave on the body of a living rabbit. In addition to the main reflected wave, they found partial reflections due to irregularities in body surface. Reflections from interior bone structures as the ribs were not observed. Harvey and McMillan (6), however, showed that shock waves will be somewhat reflected by bony structures and flow around them.

Harvey and McMillan adapted the spark shadowgram or Schlieren method to the study of shock wave behavior in tissue. They placed the tissue on or immersed in water, and the shock waves, produced by a missile striking the water, were shown to pass from tissue to water and to be reflected from tissue surfaces.

Clemedson and Criborn (2) studied the mechanical response of different parts of a living rabbit body to the impact of a high explosive shock wave. Two different types of shock waves were observed in the tissue, one of short duration was generated by a TNT charge in an open field, and one long-lasting, multi-peak wave generated in a detonation chamber. The responses were obtained by means of strain gages.

Clemedson, et al, (5), measured the velocity of a shock wave in muscular tissue by means of two barium titanate crystal pressure transducers and found the mean velocity to be 2132 feet per second, the range being 1935-2329 feet per second. It is expected that biological materials of different compositions, such as brain substance, muscle, bone, etc., will have unique and distinct shock wave transmission velocities. A sudden velocity change, then, from the movement of pressure through two different media will result in surface bruising and even perforation of linings of tissue.

The transmission of air shock waves to the central nervous system in rabbits was studied by Clemedson (1). Barium titanate pressure transducers were embedded in the brain and spinal column. He showed that the main part of the shock wave pressure is transmitted to the brain directly through the skull - the role of the blood vessels or the spine for that transmission is insignificant.

Media of varying density will impart changes to the shock wave as it passes from one medium to another. Available information from studies of blast exposure (8) show that air containing viscera and lungs are sometimes seen to be abraised and ruptured, when no other organ seems to be injured at all. Also, heterogeneity of adjoining tissue density will produce shearing due to differences in velocities imparted to them by the shock wave.

The present study was undertaken to obtain measurements of shock wave characteristics in the field of a biophysical model - pertaining specifically to the range of blast exposures comprised in our long range studies of behavioral effects. Values and graphic representations of the shock wave were obtained in free air and at the top of head, the mid-brain and thorax of the Rhesus monkey with distance and position of the explosive varying in relation to the animal's body.

Two adolescent Rhesus monkeys were instrumented with Atlantic Research, type BC-10, pressure transducers. These were surgically inserted between the skin and skull of one animal and in brain tissue and thorax of the other. Because of the large size of pressure transducers, live animals were not used. The head skin of the one animal was molded about the pressure gage and held in place with sutures. In the other animal, the gage was placed through the right eye orbit into the brain after the eye was removed. The orbit was packed with cotton and eyelids sutured. In the same animal, a second gage was inserted into the thoracic cavity between the heart and the right lung.

Three Atlantic Research piezoelectric ceramic transducers, type BC-10, with average sensitivity of 546, 517 and 530 micro-microcoulombs/psi, respectively, were used. The dimensions of this pressure transducer are: length, 30 mm and diameter, 9 mm. Calibration curves show linearity of response for these gages in the pressure range from 0-300 psi - the accuracy is better than plus or minus 1%. A pencil gage (piezoelectric type), spanned by a pair of velocity gages, was used to determine the free air pressure.

Thirty-four rounds were fired under various settings. Twenty-seven records were obtained intact and a summary of data for these are given in the several tables. Representative wave forms are also reproduced for all settings.

The results were arranged into four groups, specifying particular conditions of animal exposure of (a) the entire body, (b) a circumscribed portion of the skull, (c) head only and (d) torso only.

CONDITIONS OF ANIMAL EXPOSURE

Orientation A

Method

Two instrumented monkeys were seated in animal chairs with their heads 1.6 feet apart and 4 feet above the ground. The upper two-thirds of the torsos were covered with 3/4 inch foam rubber and canvas. The 1/2 lb. spherical charges of pentolite were positioned and detonated from two distances; 7.1 and 8.6 feet above the animals' heads. Simultaneous traces of the shock pressure waves in the ambient atmosphere, top-of-head, within-the-brain, and within-the-thorax were made on the oscillograph. Peak-overpressure, the positive duration and impulse were recorded for each round and each gage. A sixteen millimeter high-speed motion picture camera was used for documenting the fireball diameter. Wood foot-markers, for scaling purposes, were placed 6 feet apart in the close vicinity of the animals. Fig. 1 shows a general view of this setup just prior to a detonation of the charge.

Results

The velocity of pickup gage data, from the side-on position, served its purpose in that the two methods of determining free air pressure agreed fairly well with one another. Also, corresponding values between the pencil and other gages showed intershot correlations of .94 to .98 and thereby verified good reliability among the measurements.

The average fireball diameter measured approximately 5 feet. Selected time interval exposures of a detonation recording are shown in Fig. 2.

Table 1 is a summary of blast data for the 7.1 and 8.6 feet distances of the charge to the nearest gages. The incident values, as measured by the pencil gage, agree very well with estimated values for ideal conditions (Table 2) when the charge was detonated at 7.1 feet. At the 8.6 feet distance, the measured positive duration and impulse values would have shown a closer correspondence with the theoretical, had it not been for the sudden pressure rise about 1.7 milliseconds from time of detonation (pencil gage curve in Fig. 4).

As would be expected to occur, the pressure values at the reflective head surface were more than twice the measured incident (pencil gage) pressure.

Figs. 3 and 4 represent time-pressure curves of two shots as recorded by the various gages. The pencil gage produced wave forms which are typical of open air detonations. A secondary positive pressure rise can be seen at the 2 millisecond mark for the "top-of-head", "inside-head" and pencil gages.

It is probable that the pressure wave reflected from the wood frame holding the charge produced this secondary pressure rise. Ground reflection seemed to have produced the 7-8 ms. deflection in the "top-of-head" and "brain" gage wave forms. The pencil gage, positioned at a greater distance from the ground, would have picked up a smaller deflection, then, at a later time. The shock wave within the skull was multi-peaked - a phenomenon which was observed consistently throughout other conditions of exposure. The "chest" gage showed a non-peaked and long-standing overpressure.

Fig. 1. GENERAL VIEW OF SETUP FOR ORIENTATION A

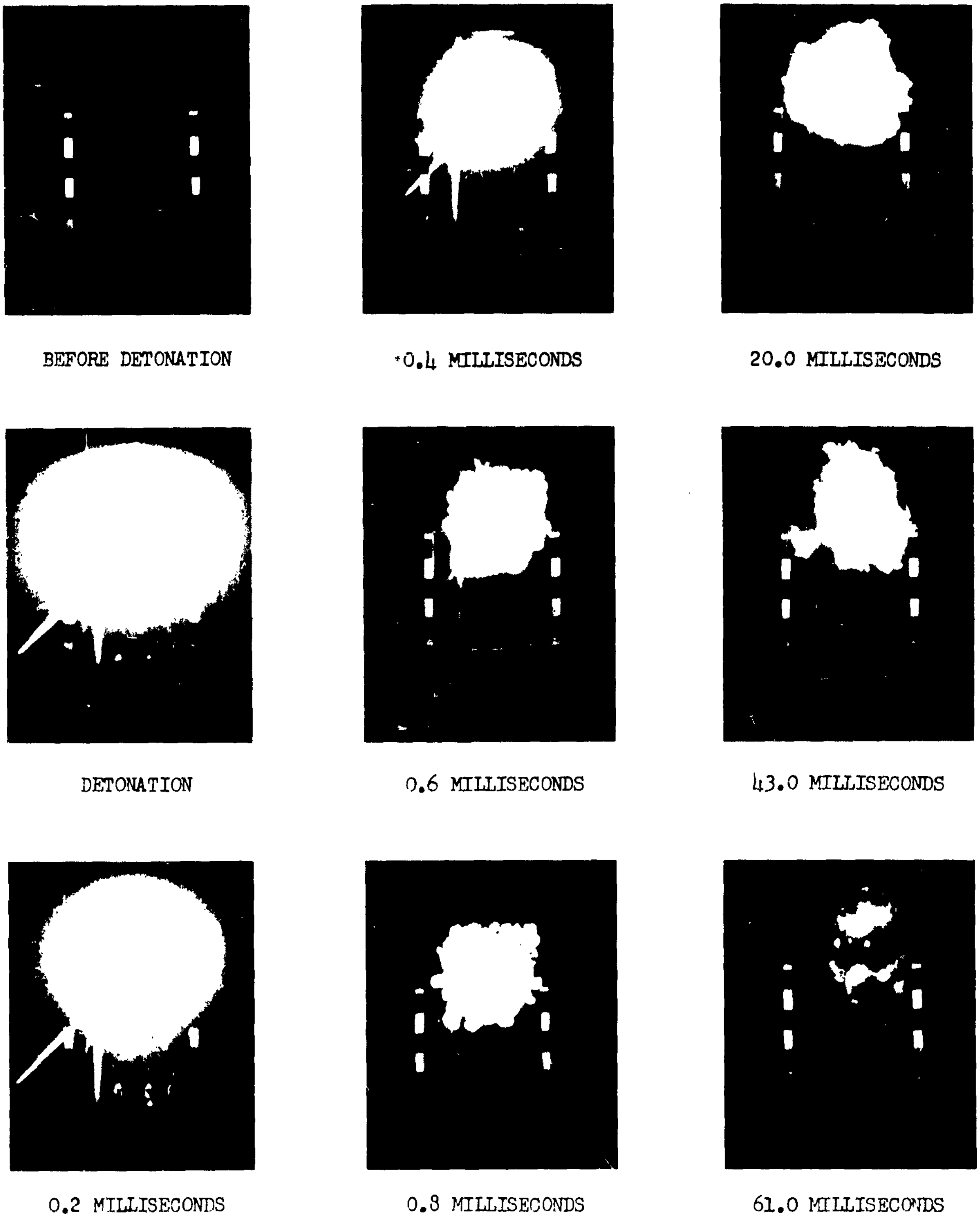


Fig. 2. SELECTED TIME FRAMES OF HIGH SPEED MOTION PHOTOGRAPHS OF A 1/2 lb. BARE CHARGE DETONATION

TABLE 1

SUMMARY OF BLAST DATA FOR ORIENTATION A

		Gage Location											
		Top-Of-Head			Brain			Thorax			Free Air		
Round No.	Charge Distance feet	Positive Duration ms	Pressure psi	Impulse psi-ms	Positive Duration ms	Pressure psi	Impulse psi-ms	Positive Duration ms	Pressure psi	Impulse psi-ms	Positive Duration ms	Pressure psi	Impulse psi-ms
2	7.1	1.6	21.0	7.7	2.1	9.2	5.8	2.6	3.2	5.3	1.6	10.0	6.4
4		1.5	26.5	10.7	1.8	10.9	6.2	2.6	3.0	4.6	1.6	9.0	5.4
6		1.4	25.5	10.6	2.1	10.5	6.7	2.5	3.2	4.9	1.5	10.0	5.6
Average		1.5	24.3	9.7	2.0	10.2	6.2	2.6	3.1	4.9	1.6	9.7	5.8
1	8.6	1.5	15.8	6.6	1.9	6.5	4.5	2.5	2.6	4.5	2.4	7.2	6.0
7		1.6	19.2	7.5	2.1	7.1	5.0	2.6	2.4	4.3	2.4	6.7	5.8
9		1.5	20.0	8.2	2.0	8.2	5.3	2.6	2.3	4.3	2.3	7.1	5.7
10		1.6	19.4	7.8	2.1	8.0	5.9	3.0	2.4	4.8	2.3	7.1	5.7
11		1.5	19.7	8.2	2.1	7.7	5.5	2.6	2.2	3.9	2.3	7.0	5.7
Average		1.5	18.9	7.7	2.0	7.5	5.2	2.7	2.4	4.4	2.3	7.0	5.8

TABLE 2

ESTIMATED INCIDENT AND REFLECTED VALUES (7)

Distance feet	Incident Positive Duration ms	Incident Pressure psi	Reflected Pressure psi	Incident Positive Impulse psi-ms
2.2	0.13	145.0	800.0	9.9
4.9	1.1	20.0	59.0	6.9
7.1	1.5	9.0	22.0	5.1
8.6	1.7	6.5	15.2	4.1
15.0	2.2	2.6	5.5	2.4

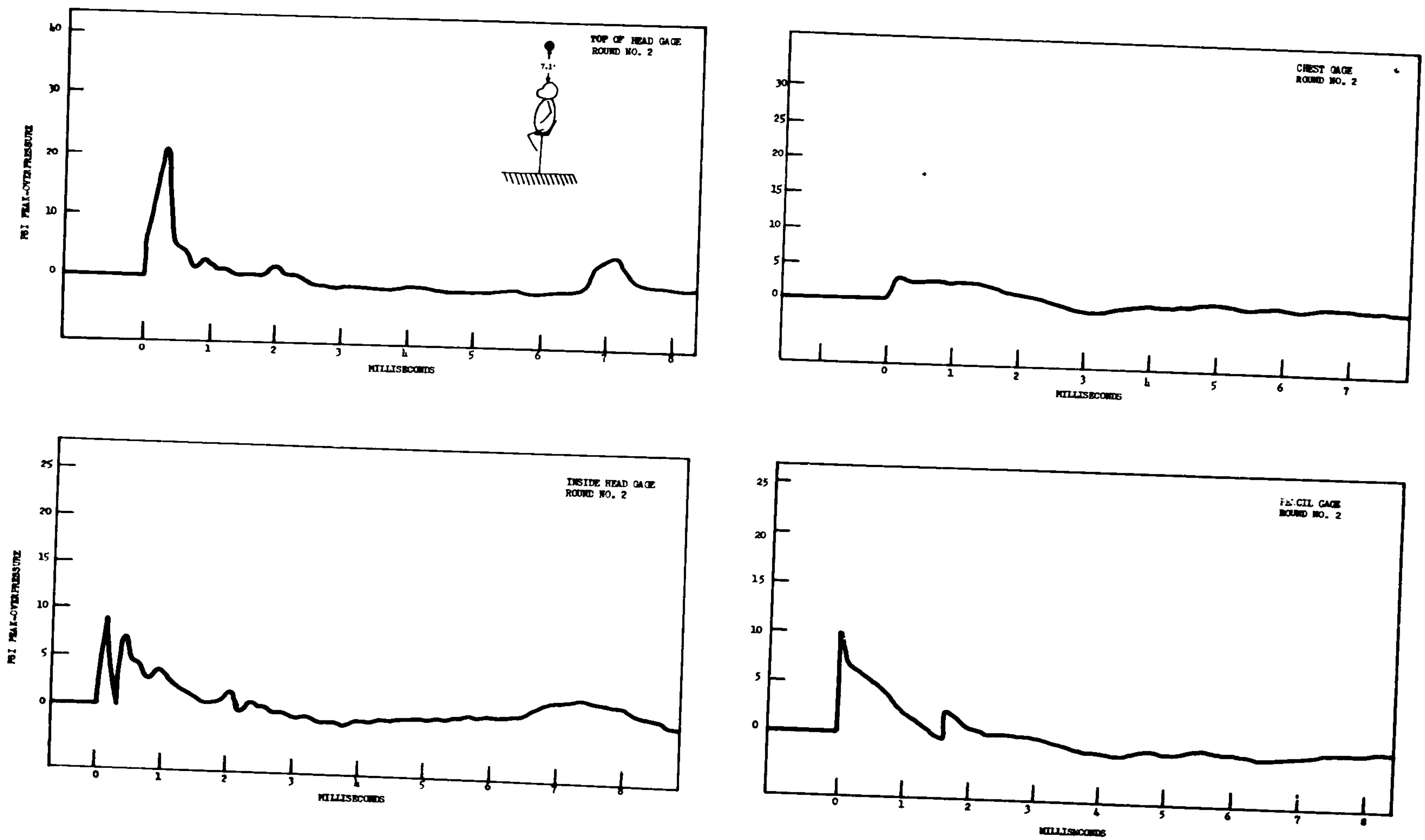


Fig. 3. TIME-PRESSURE TRACES OF DETONATION AT 7.1 FEET

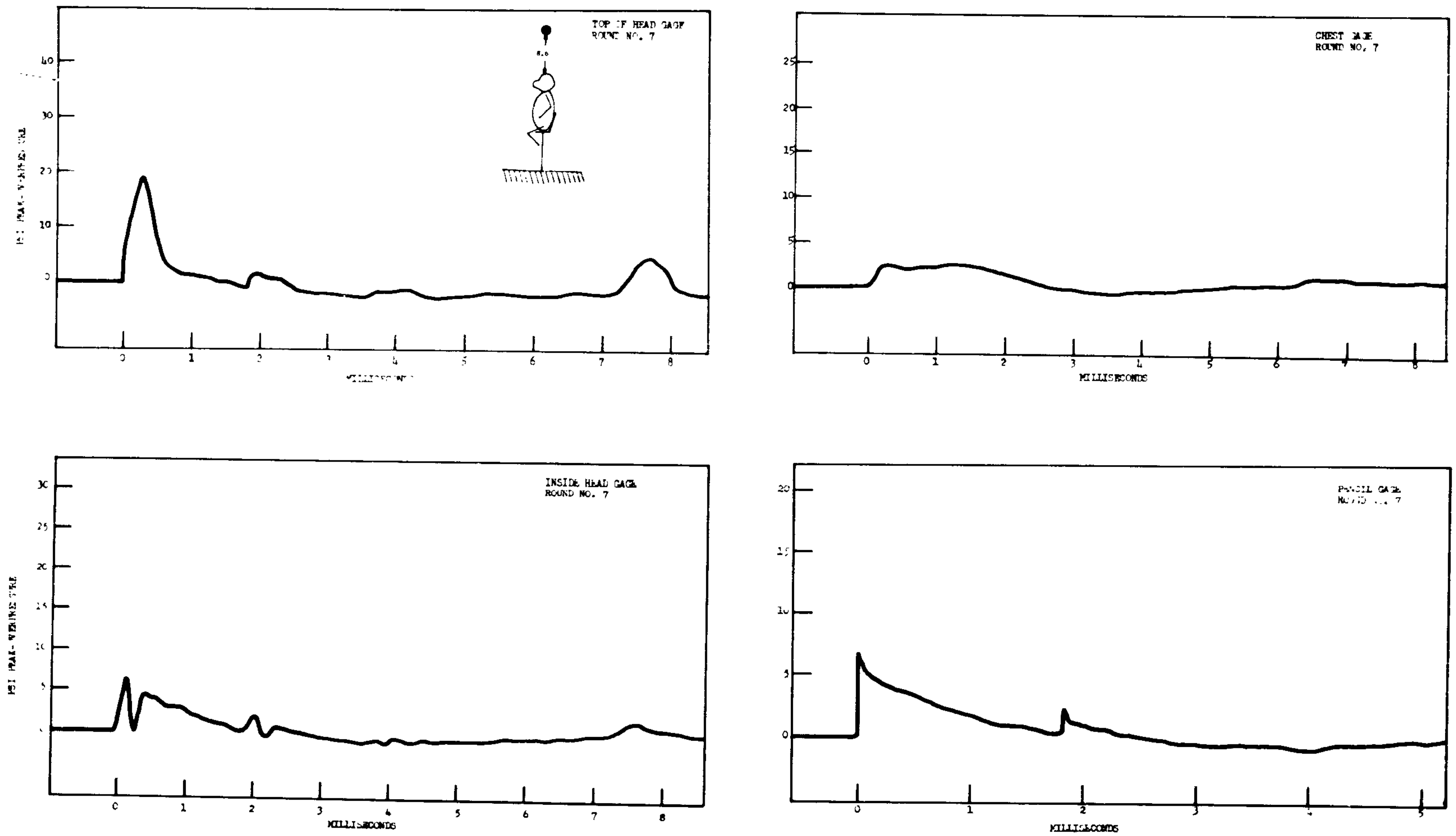


Fig. 4. TIME-PRESSURE TRACES OF DETONATION AT 8.6 FEET

Orientation B

Method

The animals were fitted securely into a specially designed chair which held the animal's head stationary. The foam rubber jacket was discarded for this and the remaining series of exposures. The chair slipped into a 3/8 inch thick, steel box which was 18 inches long, 12 inches wide and 20 inches high. The box was buried with the top at ground level. The box lid, which bolted into place, contained a 2 inch diameter opening against which the animal's head was placed. A rubber seal surrounded the perimeter of the hole and, with the head against the opening, resisted the passage of air into the container. Each animal was blasted separately with the bare charge positioned 2.2 feet above the box opening.

Results

The "top-of-head" gage did not function properly for this series and for the remaining detonations of this study. The records obtained for these rounds were very erratic, indicating something other than the blast wave was affecting the gage. Heat from the detonation probably arrived at the gage at about the same time as the blast wave, thereby distorting the pressure time trace recorded by the exposed gage.

"Estimated" incident and reflected peak overpressures for the 2.2 feet distance of charge to gage are 135 and 800 psi respectively (Table 2). The ratio of "estimated" incident peak overpressure and the empirically measured "brain" gage values for rounds 13 and 14 is close to being one to one (Table 3). The same ratio existed for the low pressures obtained in Orientation A.

The "brain" gage in the animal's head, which was encased within the steel container, gave a record of pressure oscillations not uncommonly seen in shock tube detonation (Fig. 5). The recorded pressures in the container "protected" thorax were very low compared to those recorded in the partially "unprotected" brain.

TABLE 3

SUMMARY OF BLAST DATA FOR ORIENTATION B

		GAGE LOCATION					
		CHEST			MID-BRAIN		
Rd. No.	Charge Dist. ft.	Pos Dur ms	Press psi	Impulse psi-ms	Pos Dur ms	Press psi	Impulse psi-ms
12	2.2	-	-	-	4.5	99	97
13		4.2	3.4	7.8	6.3	124	128
14		4.3	2.4	5.3	5.2	128	80
15		4.2	2.3	5.1	5.3	91	77
	Average	4.2	2.7	6.1	5.3	110	95

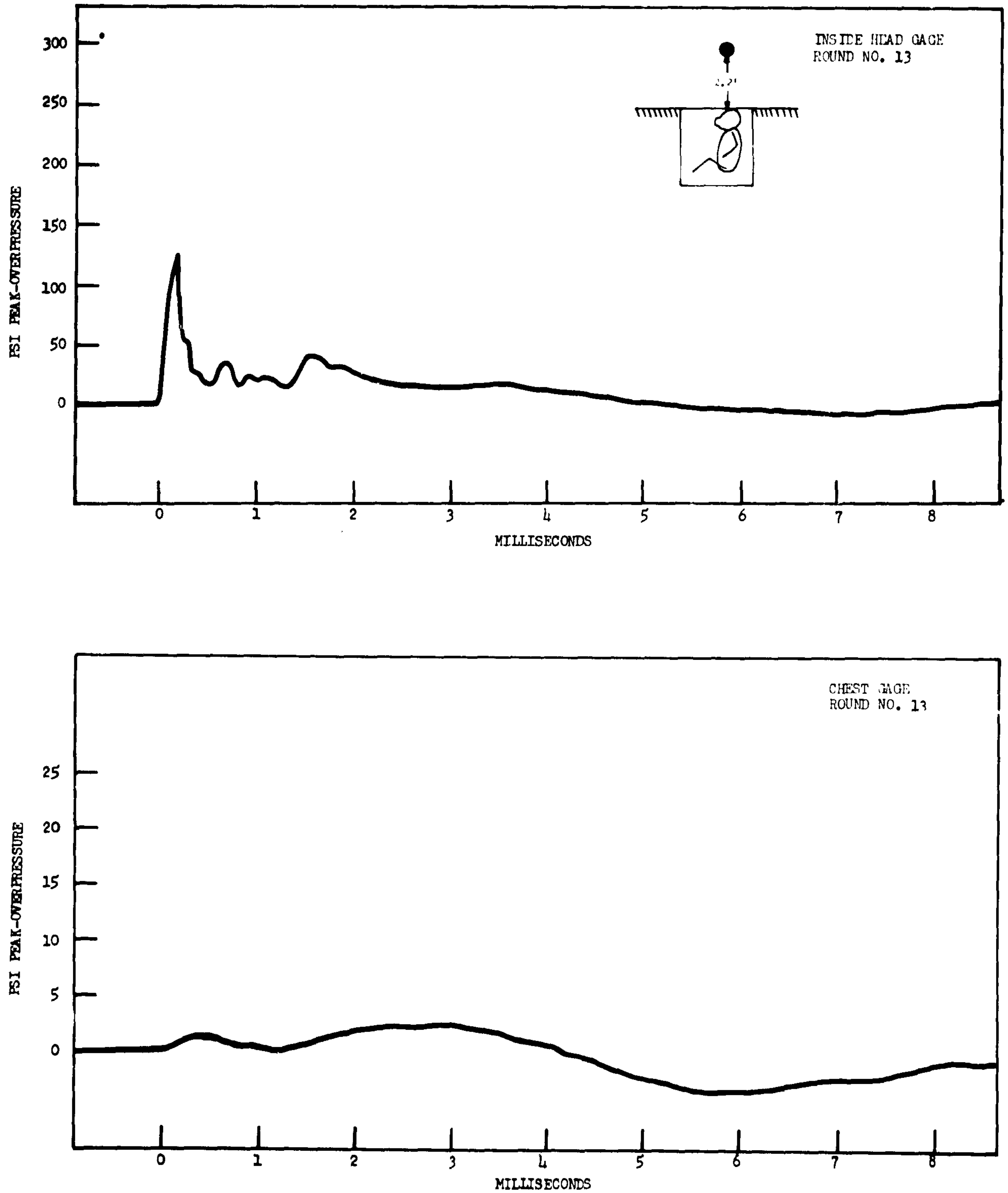


Fig. 5. TIME-PRESSURE TRACES OF DETONATION AT 2.2 FEET

Orientation C

Method

The box, used in Orientation B, was suspended with its topside 5.2 feet above the ground. The entire head was exposed in this sequence of shots, while the body remained protected within the steel container. The animal's neck was wrapped initially with plaster of paris bandage and, while still wet, a 1/4 inch rubber gasket was embedded into it to create a seal for the box interior. The bare charges were positioned 5.2 feet above ground and for distances of 15.0, 4.9, and 2.2 feet from the back of the animal's head. Additional shots were made 2.2 feet above the animal's head and, except for the box resting on the ground, the conditions were similar.

Results

Table 4 shows the blast summary data for rounds 21 through 28. With the entire head outside the box and the remainder of the body within, the "brain" shock wave forms, from the sideward detonations, were similar to those found in Orientation A (Figs. 6, 7, & 8). The pressures measured in the chest were barely perceptable and did not significantly increase as the distance to charge was reduced. Detonations made in the downward direction created significantly different peak overpressures and rise times than any other made at the same distance but different setting (Fig. 9). Both shots, 27 and 28, made in this fashion formed shock waves which were almost identical in appearance and amplitude.

Orientation D

Method

The box was suspended upside down. Both the hole side, which now faced the ground, and charge were positioned 5.2 feet above the ground. The animal's head was placed within the container while the remainder of the body extended freely downward. The distance of the charges were, respectively, 15.0, 4.9 and 2.2 feet from the body surface of the animal.

Results

When the body was directly exposed and head protected, both head and chest gages exhibited non-peaked positive deflections and gradually increasing shock fronts except for high pressure exposures, when the reverse was recorded (Table 5) (Figs 10, 11, & 12). The positive duration of the brain wave form was consistently shorter than that of the chest. The gage in the "container protected" head tended to show increasingly higher amplitudes in peak overpressure as the outside pressure increased, an occurrence which did not reveal itself in the gage of the similarly "container protected" chest of Orientation C.

TABLE 4

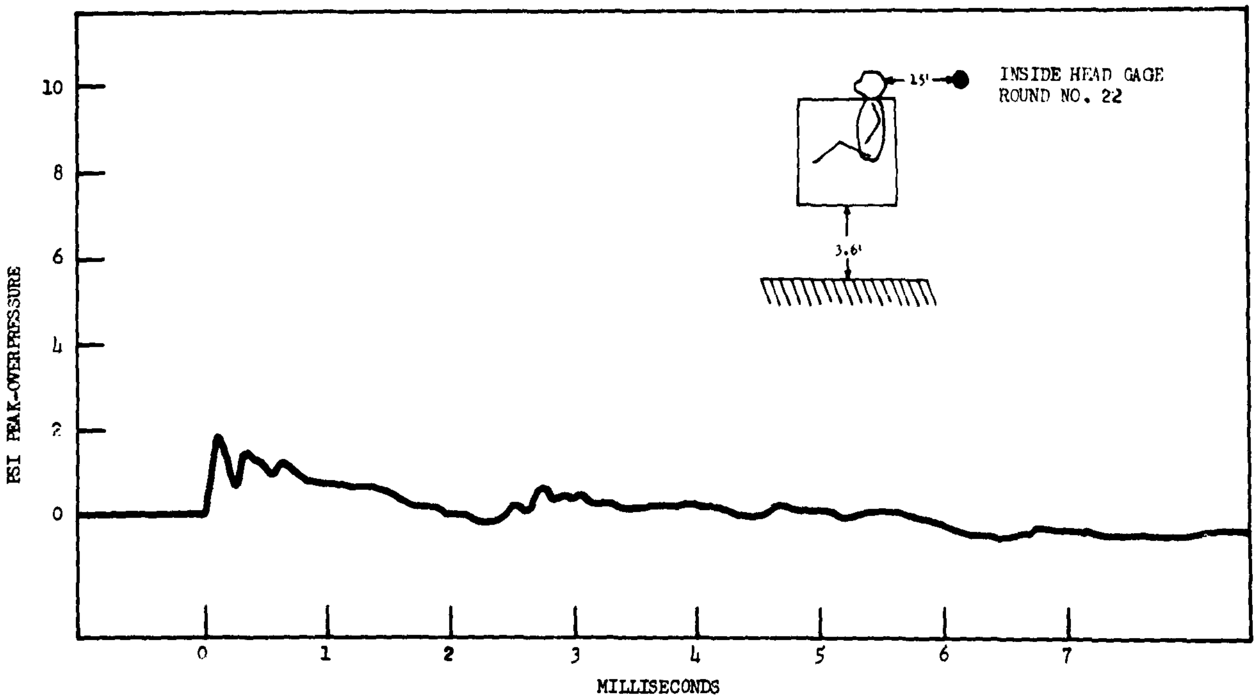
SUMMARY OF BLAST DATA FOR ORIENTATION C

		GAGE LOCATION						
		THORAX			BRAIN			
Rd No.	Charge Dist. ft.	Pos Dur ms	Press psi	Impulse psi-ms	Pos Dur ms	Press psi	Impulse psi-ms	Blast Direction
21	15.0	4.6	0.3	1.1	1.9	1.6	1.5	Sideward
22		5.0	0.5	1.4	2.0	1.8	1.5	
Average		4.8	0.4	1.3	1.9	1.7	1.5	
23	4.9	6.1	0.6	2.4	1.8	15.2	5.0	Sideward
24		6.0	0.6	2.1	1.9	15.9	5.5	
Average		6.0	0.6	2.2	1.9	15.5	5.2	
25	2.2	6.1	0.6	2.3	0.15	108.0	8.0	Sideward
26		6.1	0.6	2.5	0.16	129.0	10.7	
Average		6.1	0.6	2.4	0.15	119.0	9.3	
27	2.2	6.5	0.9	2.9	0.7	62.0	171.0	Downward
28		6.6	0.9	2.9	0.9	52.0	166.0	
Average		6.5	0.9	2.9	0.8	57.0	169.0	

TABLE 5

SUMMARY OF BLAST DATA FOR ORIENTATION D

		GAGE LOCATION					
		THORAX			BRAIN		
Rd. No.	Charge Dist. ft.	Pos Dur ms	Press psi	Impulse psi-ms	Pos Dur ms	Press psi	Impulse psi-ms
20	15.0	4.7	1.7	4.1	Lost	0.1	Lost
30		4.8	1.7	4.2	1.2	0.1	0.1
Average		4.7	1.7	4.1	1.2	0.1	0.1
31	4.9	2.5	9.1	13.0	1.2	0.9	0.6
32		2.5	9.0	14.3	1.1	1.0	0.6
Average		2.5	9.0	13.7	1.1	0.9	0.6
33	2.2	2.6	131.0	122.0	1.0	4.6	2.3
34		9.8	253.0	270.0	1.3	7.0	3.2
Average		6.2	192.0	196.0	1.2	5.8	2.8



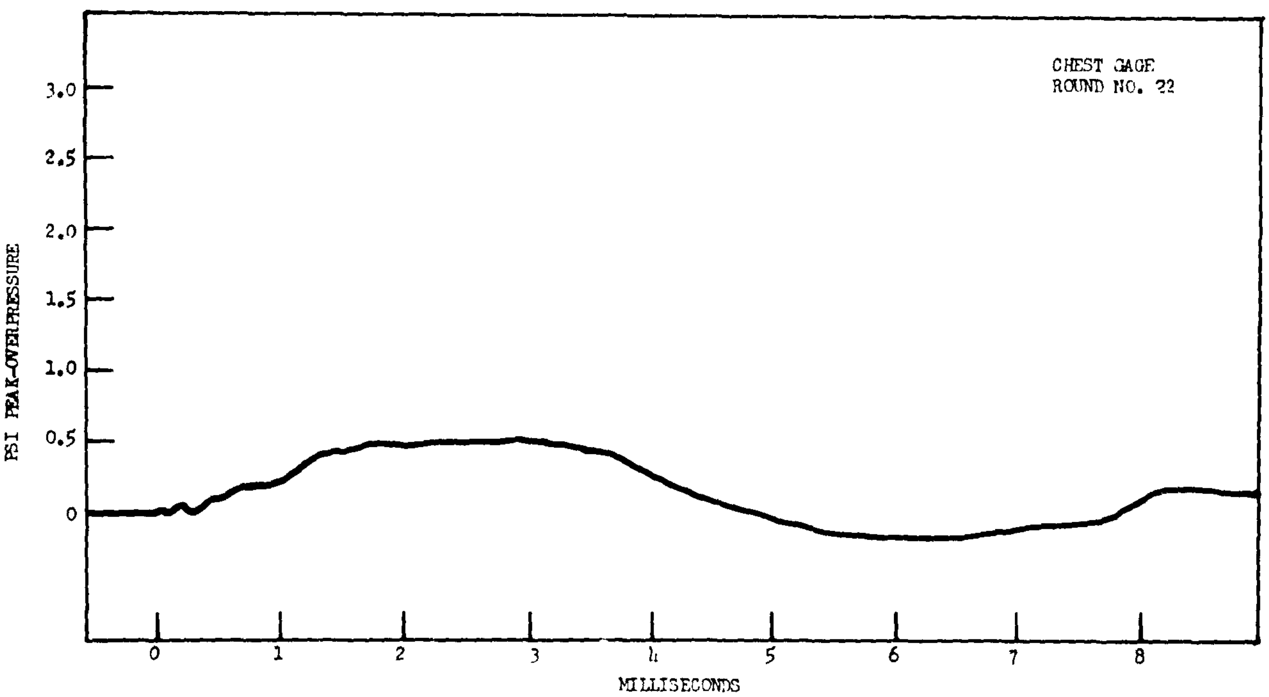
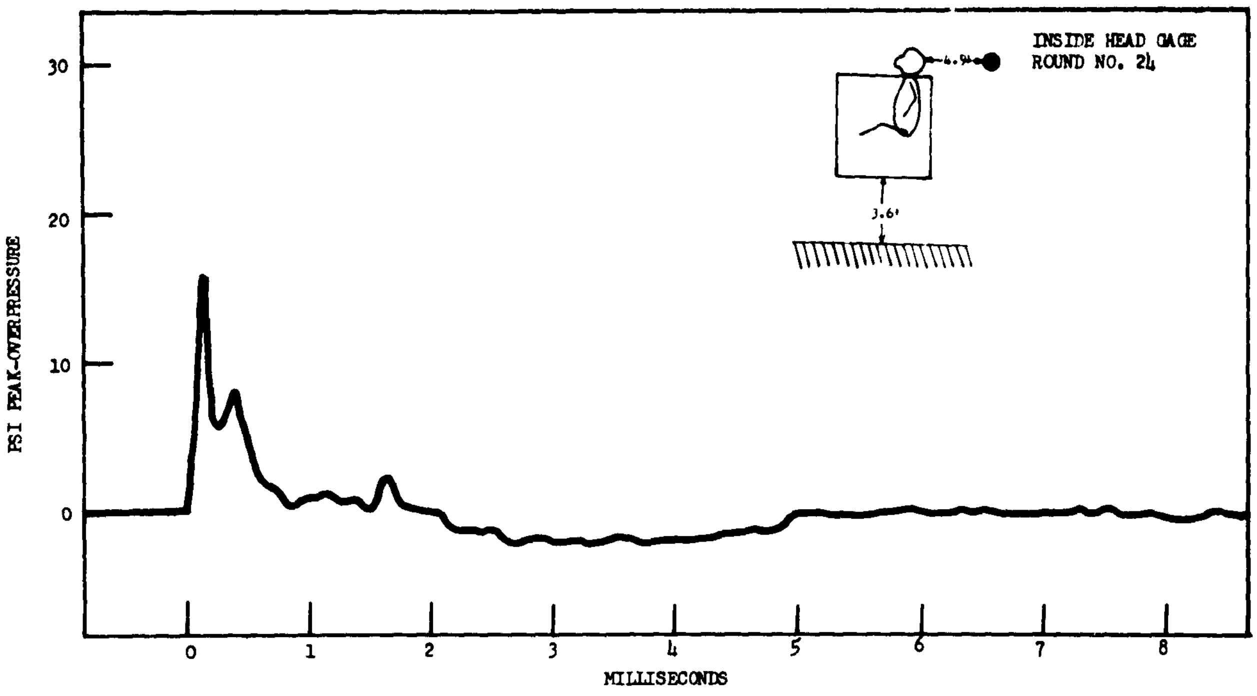


Fig. 6. TIME-PRESSURE TRACES OF DETONATION AT 15 FEET, SIDEWARD



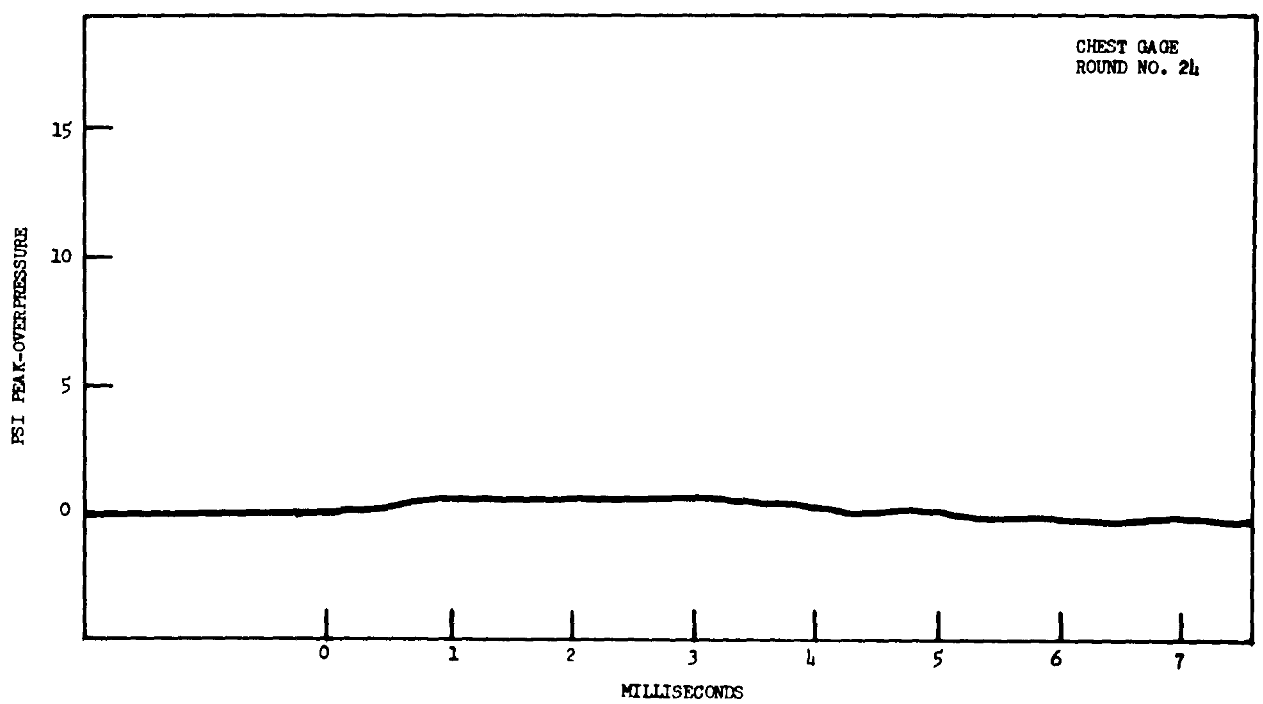
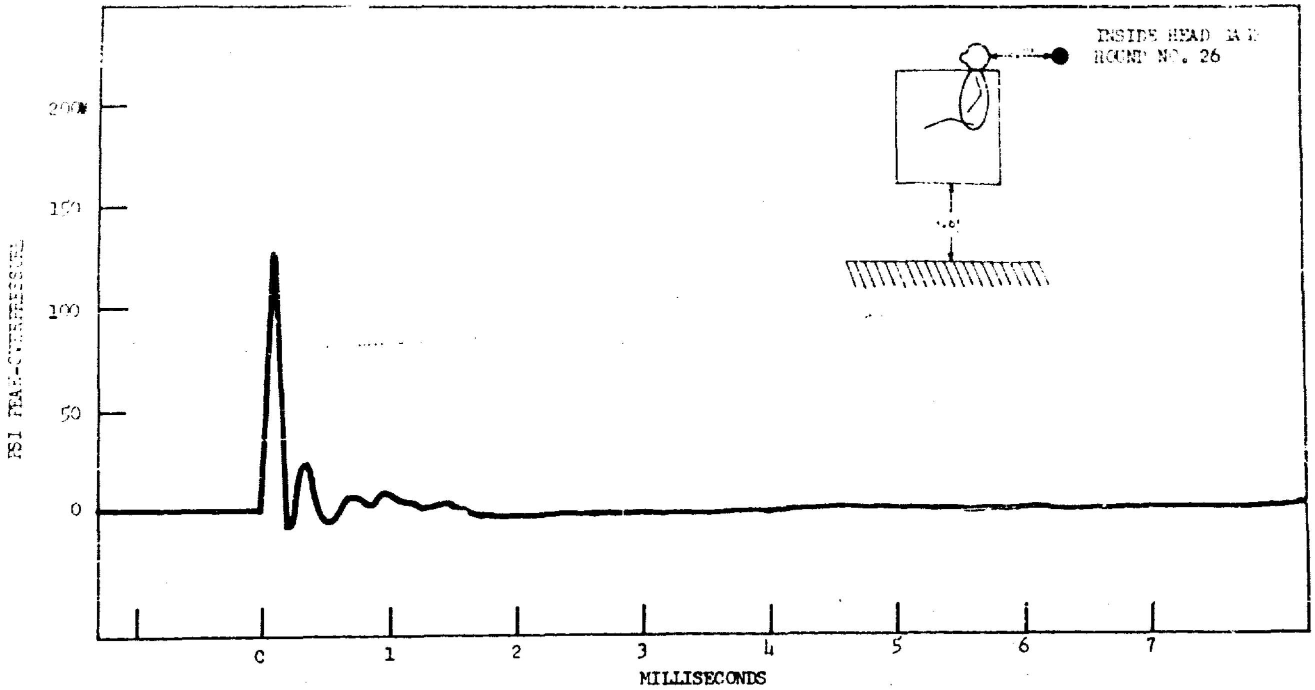


Fig. 7. TIME-PRESSURE TRACES OF DETONATION AT 4.9 FEET, SIDEWARD



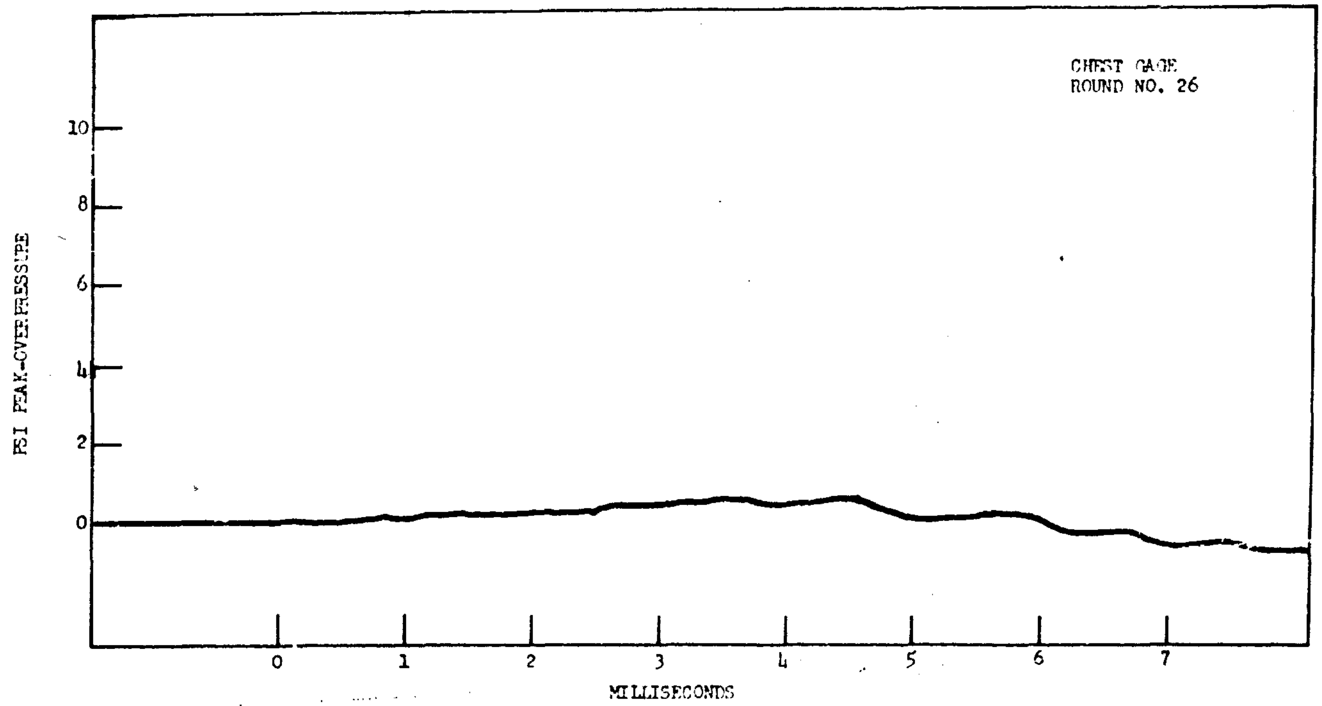
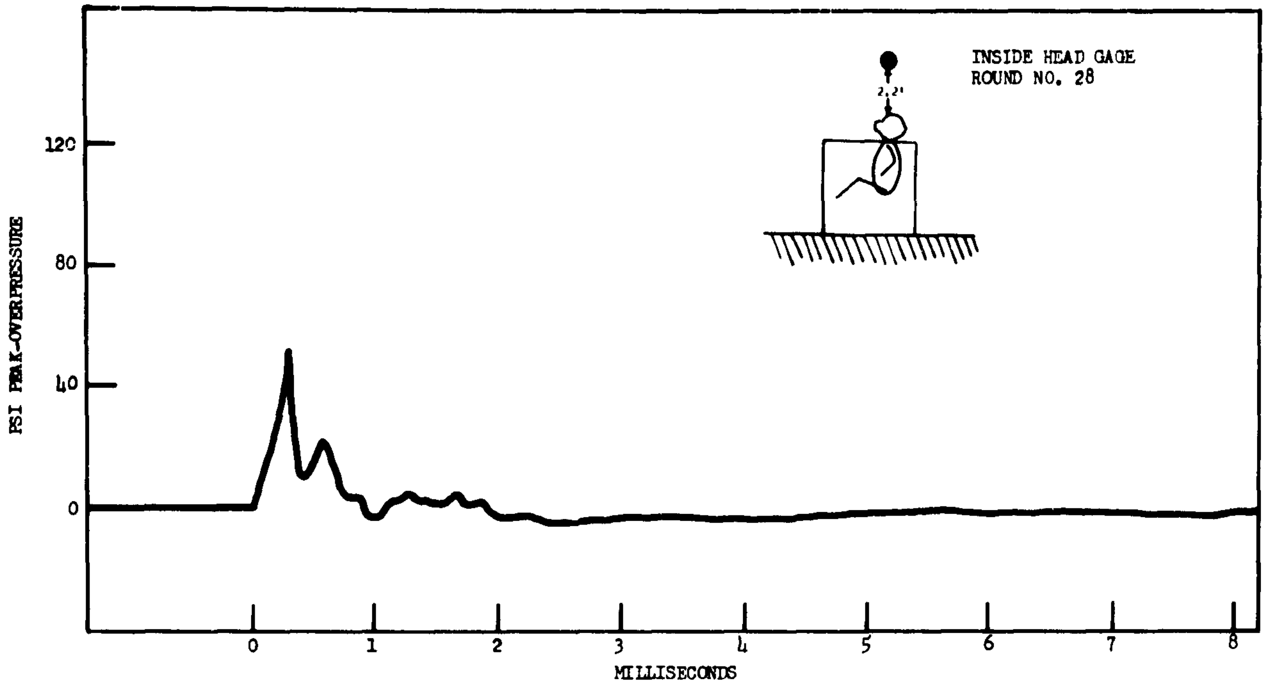


Fig. 8. TIME-PRESSURE TRACES OF DETONATION AT 2.2 FEET, SIDEWARD



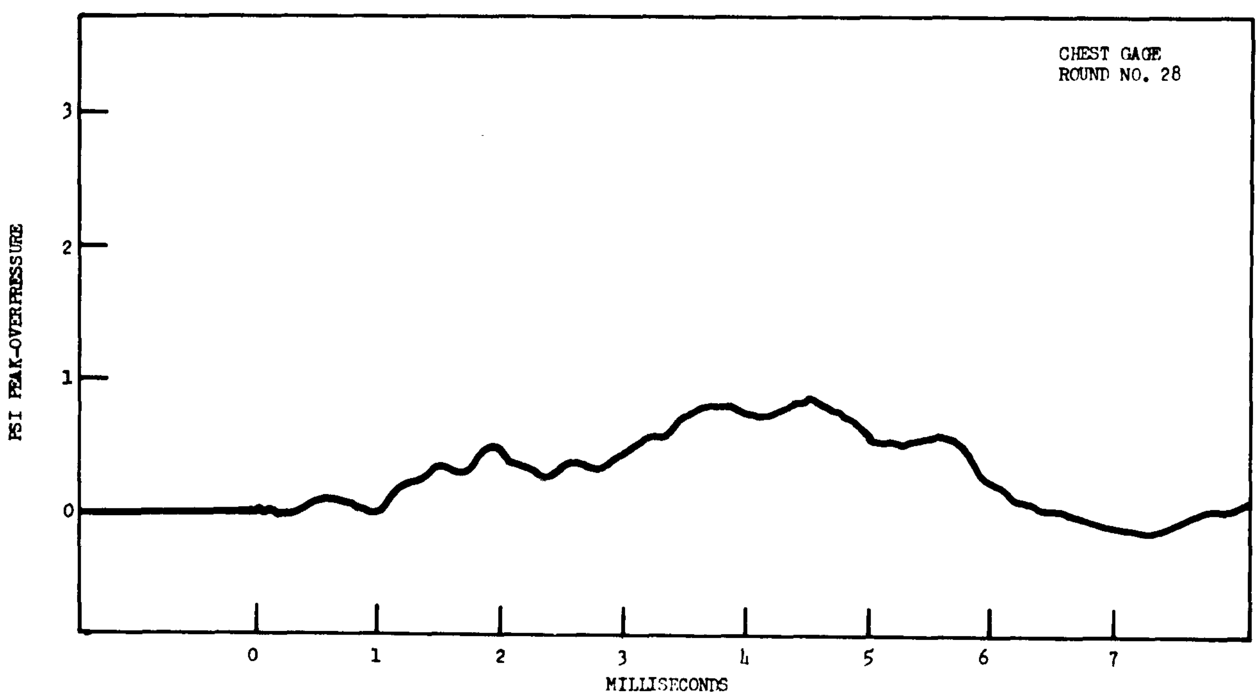
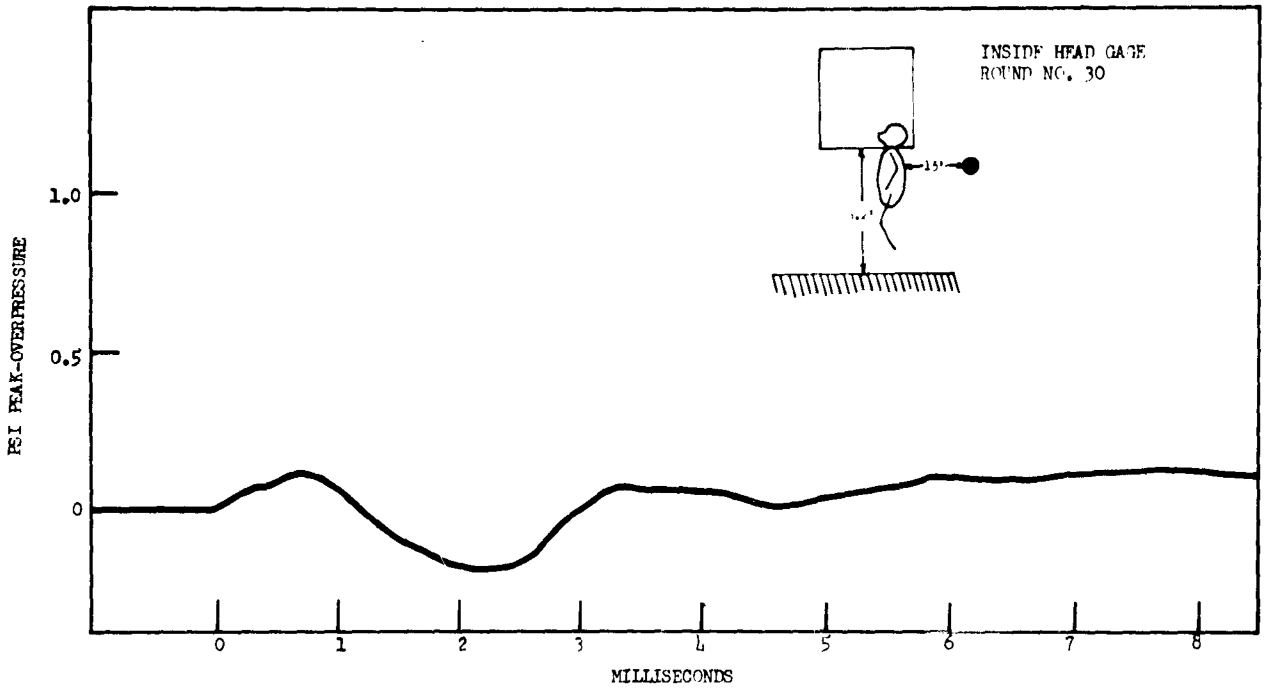


Fig. 9. TIME-PRESSURE TRACES OF DETONATION AT 2.2 FEET, DOWNWARD



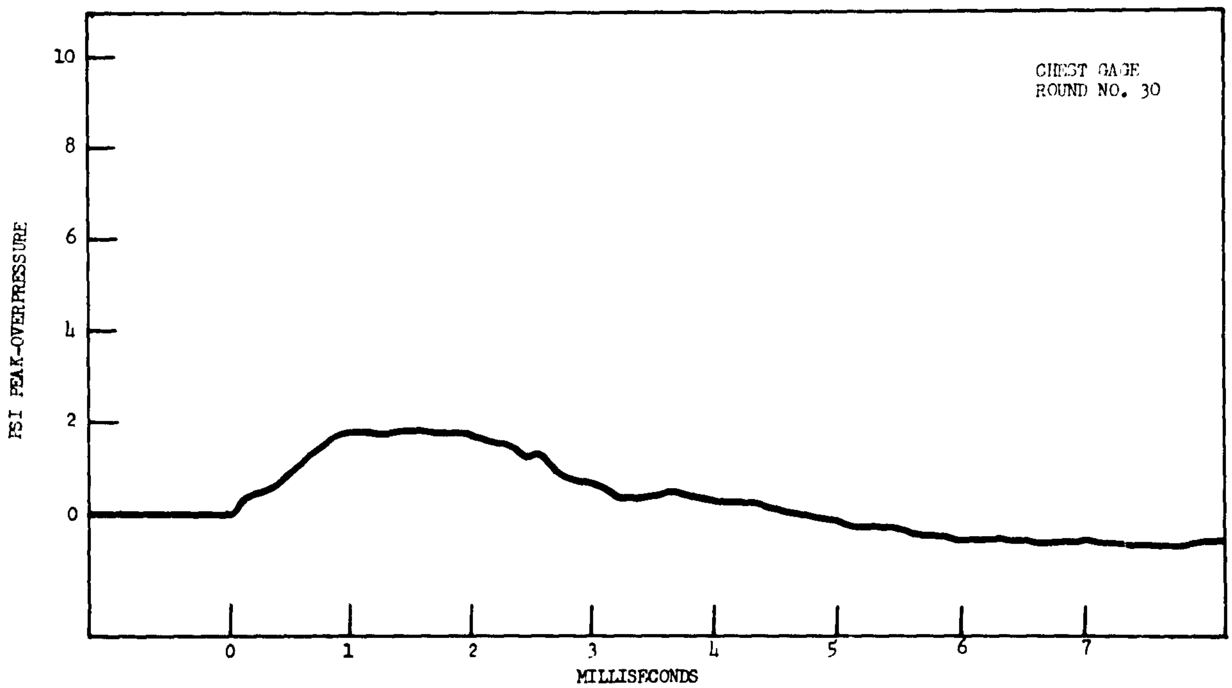
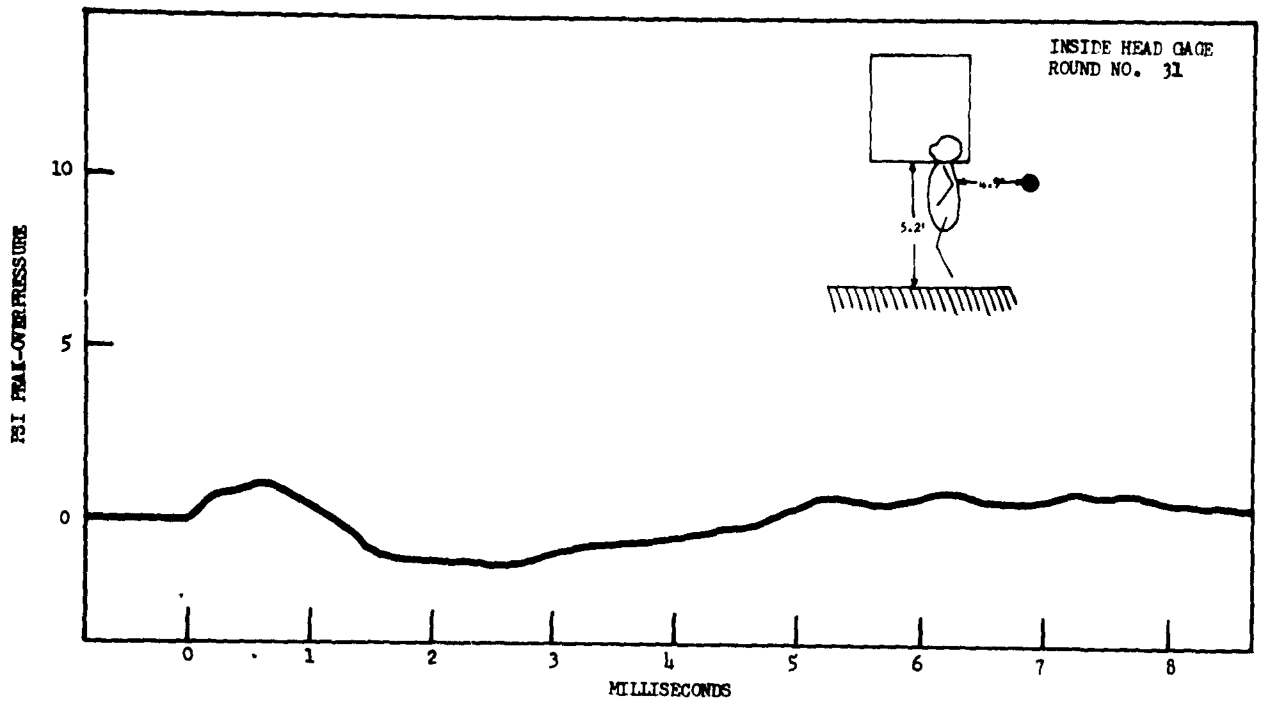


Fig. 10. TIME-PRESSURE TRACES OF DETONATION AT 15 FEET



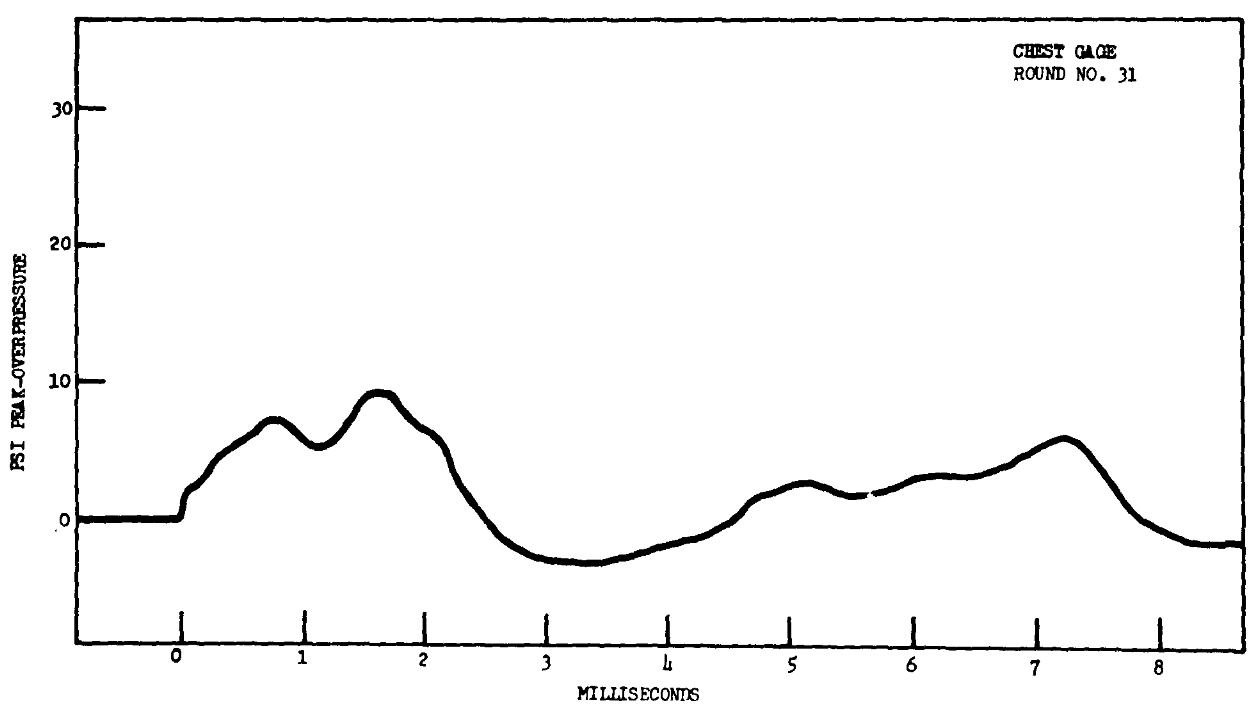


Fig. 11. TIME-PRESSURE TRACES OF DETONATION AT 4.9 FEET

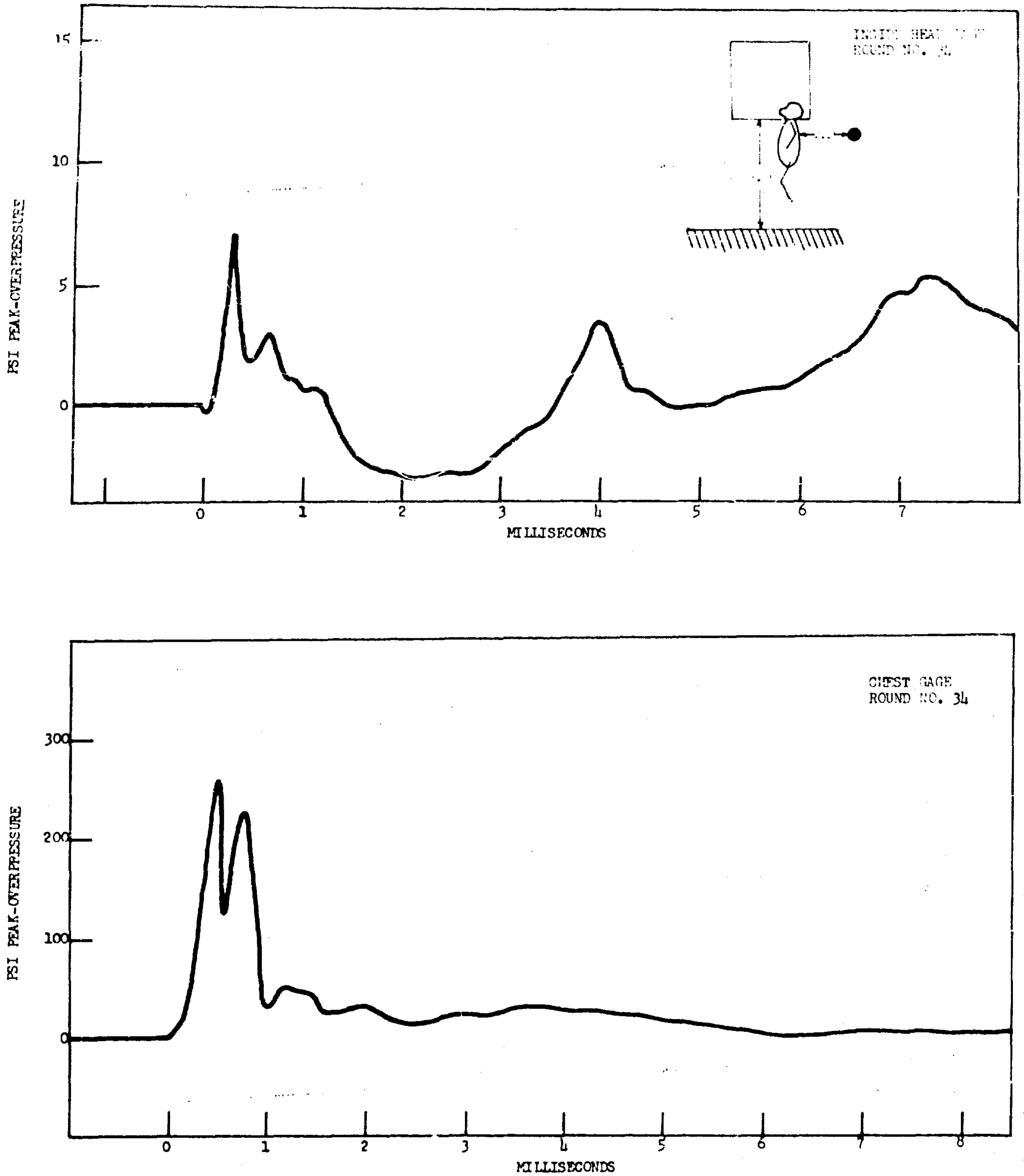


Fig. 12. TIME-PRESSURE TRACES OF DETONATION AT 2.2 FEET

DISCUSSION

The physics governing the distribution of shock wave energy about and within a reflective surface, such as the animal's skull, is complicated and not well understood. The complexity of the problem was emphasized in consistently obtaining almost identical values of peak overpressure in free air and in the brain, even though Harvey and McMillan (6) demonstrated that the incident pressure wave is reflected from the skull. To further the understanding of reflective, absorptive, and distributive properties of the shock wave about and within animal tissue, comparative animal forms possessing differences in shape, size and composition of tissue material would serve well.

The mechanical properties of the skull may be largely responsible for the shock wave reflections which were recorded by the gage embedded in the brain of the monkey. A force of sufficient magnitude, when applied to the bone of the skull, will produce a compression along the vertical plane to the point of impact. If a small circumscribed portion of the skull is acted upon by a strong wave, as in the case of round No. 13, the resulting response is similar to one caused by the rapid application of a blunt instrument to the head. The pressure wave produces a local indentation at the site of impact, which is followed by an immediate deformation of the entire skull. In total head exposure, the reaction of the entire skull is dependent, in addition to the initial local impact of the shock wave, upon a continued exerted force over its entire external surface.

The portion of the pressure wave transmitted through the skull, if it conforms to the action of a pressure pulse within a closed unit, will reflect repeatedly against the bony inner surfaces of the skull. This principle can account for the smaller pressure wave oscillations found in the records.

The shock wave passing through the abdomen or the thoracic cavity is quickly attenuated. The damping quality of such tissue is exemplified in two of our series of exposures. First, with the head exposed and the body protected, the force acting caudally along the vertical plane dissipated before it reached the lower thorax. Secondly, in the case where the head was placed inside the box, the strong shock wave striking the shoulder and neck regions of the animal had only to travel three inches upwards through the neck to the brain before the shock wave amplitude was shown to be greatly reduced.

The nature of changes to the shock wave as it is transmitted from one medium to another has been lightly explored in this study, while the mechanisms of blast injury have not been touched upon. A knowledge of the latter, we suspect, will await a more comprehensive and systematic exploration of the former.

SUMMARY

Shock waves, generated by open air detonations at varying distances, were recorded by means of gages located in the free air field, top-of-head, inside the brain, and thorax of two Rhesus monkeys. The nature of changes in shock wave forms and characteristics was studied in relation to pressure movements from an air medium to a biophysical one. Four conditions of animal exposure were studied: (1) the entire body, (2) a circumscribed portion of the skull, (3) head only and (4) torso only. The "top-of-head" gage showed wave forms with relatively slower rise time but faster recovery to ambient pressure level than that of the typical pencil gage in air. The gage in the brain recorded short period, large pressure oscillations which were quickly damped and, except for the oscillations, the wave form fairly follows that recorded in free air. The "chest" gage, showing the greatest change, gave long duration rise times to peak overpressure and return; oscillations, characteristic of the "brain" gage, were absent. Transmitted strong shock waves were shown to be quickly damped by the biophysical media. The problem complexity of shock wave reflection and transmission of energy is emphasized.

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THE PROPAGATION OF AIR SHOCK WAVES ON A BIOPHYSICAL MODEL, John J. Romba and Paul Martin
Technical Assistance of Wilson Dorsey
Tech Memo 17-61 OMS Code 5010.11.819 Unclassified

Shock wave characteristics were studied in the field about and within the Rhesus monkey body form. Measurements were obtained in free air, top of the animal's head, the mid-brain and the lower thorax; with distance and position of the explosive varied in relation to the animal's body. The study of shock wave transmission from one body level to another was accomplished and the problem complexity of shock wave energy distribution in the field of the organism was emphasized. Shock wave forms were observed to be uniquely characteristic of the medium through which shock wave transmission occurred. In addition, body tissue was found to greatly attenuate the shock wave. The study of shock wave characteristics in and about biophysical media is believed to be relatively unexplored.

UNCL

1. Air Shock Waves
   Biophysical Model
2. Biophysical Model
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3. OMS Code 5010.11.819
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